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APPLICATION OF A PREDICTIVE CHANNEL SHOALING AND MIGRATION MODEL, M3D, TO ST MARYS ENTRANCE, FLORIDA

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The growing need to deepen, widen, and reorient navigation channels through coastal inlets to accommodate deep-draft vessels calls for improved predictive tools. A numerical model, M3D, which represents marine sediment dynamics with sufficient resolution to analyze and predict patterns of shoaling and scour, has been developed and applied to simulate channel survey data collected at St. Marys Entrance, FL-GA, USA, with good results. The observed systematic decrease in shoaling rate with distance offshore is correctly simulated and can be explained by the dependence of bottom stresses on water depth and the ambient grain size.

1. Introduction

The U.S. Army Corps of Engineers (USACE) maintains channels through more than 150 federally authorized coastal inlets. Many of these channels will be deepened in the future or modified to improve channel reliability (amount of time safe navigation can occur) in accommodation of larger vessels (Hess 2001). Predictive tools are required to estimate operation and maintenance dredging for channels to be modified, as well as to connect the sediment-transport processes between the navigation project and the adjacent beaches. Few engineering predictive tools are available for conducting studies to understand and predict channel shoaling or infilling, channel migration, scour near jetties, and morphologic response.

Currents, waves, sediment transport, and morphology form a coupled dynamic system with multiple levels of nonlinear feedback between the components. Waves and currents interact and cause the entrainment of bottom sediment. Currents distort the propagation of waves, and waves change the structure of the current boundary layer. Morphodynamic change, produced by gradients in sediment transport rates, alters the waves and currents and their subsequent driving of sediment transport. Despite these complex and non-linear relationships, understanding of these processes has grown considerably. If guided by reliable laboratory and field data, understanding is sufficient to provide a basis for developing predictive tools.

The numerical circulation model M2D (Militello et al. 2004, and references therein) developed in the USACE Coastal Inlets Research Program (CIRP) has proven to be efficient, robust, and reliable for simulating circulation in complex coastal environments. It provides a solid hydrodynamic foundation for developing a general-purpose sediment transport and morphodynamic model. The M3D model is a three-dimensional extension of the M2D depth-averaged technology.

The M3D model hydrodynamic and sediment transport components were tested against numerous data sets as part of this study. The model successfully reproduced the time-dependent flow and suspended sediment transport measurements in flow tunnel experiments of Ribberink, et al. (1994) and the flow and suspended sediment vertical profiles and time series data from the field experiments of Wright (1999).

M3D was applied to simulate in-filling rates at the St. Marys Entrance channel to test the morphodynamic component and the general applicability of M3D to coastal problems. The model simulation demonstrated the influence of water depth and grain size on the calculated sediment transport rates. The systematic decrease in shoaling rates with distance offshore is correctly simulated with the model and can be explained by the dependence of bottom stresses on water depth and the ambient grain size, as discussed below.

2. M3D Model Description

The M3D model was developed as a CIRP research activity. The basis for the M3D model development is an explicit merging of M2D and the SLICE numerical model. SLICE was developed by URS Corp. as part of the Office of Naval Research (ONR) project STRATAFORM (Nittrouer 1999). SLICE is a time-dependent, two-dimensional coupled process-based hydrodynamic, sediment transport, and morphodynamic change model. It represents short to medium (days to centuries) time-scale evolution of continental shelf morphology and stratigraphy. SLICE simulates sediment erosion, transport, deposition, and bed elevation changes for arbitrary initial bed profiles in response to wave and tidal forcing. The model includes representations of a) wave-current boundary-larger interaction, b) effects of vertical sediment suspension concentration gradients on the turbulence structure, c) bed armoring, d) bed-form generation and bottom stress partitioning, e) multiple grain sizes, f) both suspended and bed load sediment transport, and g) fully coupled morphological changes.

The M3D model resulting from the combined M2D and SLICE models contains specialized methods and elements to provide accurate and efficient numerical solutions. The two most characteristic features of M3D are a highly refined mesh near the bed and the incorporation of surface wave properties in the turbulence model. This approach allows detailed and continuous representation of currents and sediment transport through the near-bed wave-current boundary layer. The M3D model resolves the horizontal and vertical directions and is based on a numerical solution to the Reynolds-Averaged Navier-Stokes equations (RANS) with the shallow water assumptions (i.e. hydrostatic pressure). The basic hydrodynamic equations solved are, in standard notation:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial x}+\frac{\partial uw}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial x}=\frac{\partial}{\partial x}K_x\frac{\partial u}{\partial x}+\frac{\partial}{\partial y}K_y\frac{\partial u}{\partial y}+\frac{\partial}{\partial z}K_z\frac{\partial u}{\partial z}+fv \qquad (1)$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial vw}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial y}=\frac{\partial}{\partial x}K_x\frac{\partial v}{\partial x}+\frac{\partial}{\partial y}K_y\frac{\partial v}{\partial y}+\frac{\partial}{\partial z}K_z\frac{\partial v}{\partial z}-fu \qquad (2)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\,, \qquad \frac{\partial p}{\partial z}=-\rho g \qquad (3)$$

Turbulence processes are described by a $k-\ell$ turbulence closure scheme. The $k-\ell$ model is based on a differential equation for the turbulent kinetic energy k and an algebraic description of the turbulent length scale ℓ. The turbulence model is coupled to the sediment transport model to represent density stabilization of turbulence mixing due to variation in the vertical density field (salinity or suspended sediment).

The transport model (sediment, salinity or any other scalar transport) is based on the basic time-dependent scalar transport equation (conservation of mass, advection, and diffusion) with enhancements to represent sediment settling, erosion and deposition. Erosion is determined as a function of the hydrodynamic stress at the bed. The calculated hydrodynamic stress is based on the total bed roughness, which may include the effects of ripples and other bedforms. A separate module predicts the bedforms based on wave and current conditions. If bedforms are present, the hydrodynamic bed stress is partitioned into form and shear components for predicting erosion. Multiple grain sizes are represented, including both cohesive and non-cohesive particles.

The morphodynamic change model is based on a variation of Exner's equation and is coupled to a bed-armoring algorithm (Reed et al. 1996). Together, they track changes in bed elevation and grain size composition. For long-time simulations, the morphodynamic changes are reflected in the hydrodynamic model by changing the bottom profile. In addition to the three basic model components (hydrodynamics, transport, and morphology), the model also includes representation of the time evolution of the bed. This allows the sediment grain-size distribution at the bed to be known over the whole domain for each time-step. Resolution of the grain size distribution in the bed allows bed armoring to be tracked, which greatly improves the validity of the computed erosion, transport, and deposition of all sediment size classes.

M3D is designed to be a general-purpose, process-based local coastal hydrodynamic, sediment transport and morphodynamic model. It can be applied in a variety of coastal settings including channels approaching inlets from both the seaward and landward sides, providing time-dependent channel response both o event-scale and long-term waves and to wind and current forcing.

3. Sediment Transport Validation

The M3D model hydrodynamic and sediment transport components were tested against numerous data sets. The laboratory data sets of Ribberink et al. (1994) and field measurements of Wright (1999) were used for the validation.

The model successfully reproduced the time-averaged suspended sediment profile measurements in flow tunnel experiments of Ribberink, et al. (1994). The experimental results represent a 1-m wave with 5-s period over a bed of 0.2 mm quartz sand. Figure 1 compares model predictions for a simulation of these conditions with the measurements, showing excellent agreement.

The model was also configured to simulate the measured near-bottom velocity and suspended sediment profiles collected by Wright (1999) during a tripod deployment as part of the STRATAFORM Project. The tripod was deployed in about 12 m water depth off the coast of Virginia over a bed of poorly sorted sands, silts and clays. Due to the high clay content, we represented the bed as cohesive sediment in the model simulations. Figure 2 shows a

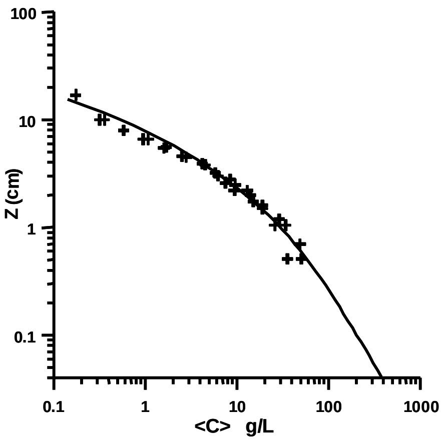

Figure 1. Comparison of measured (Ribberink et al., 1994) and simulated wave averaged profiles.

comparison of the vertical profiles of velocity and suspended sediment concentration at two points during the event.

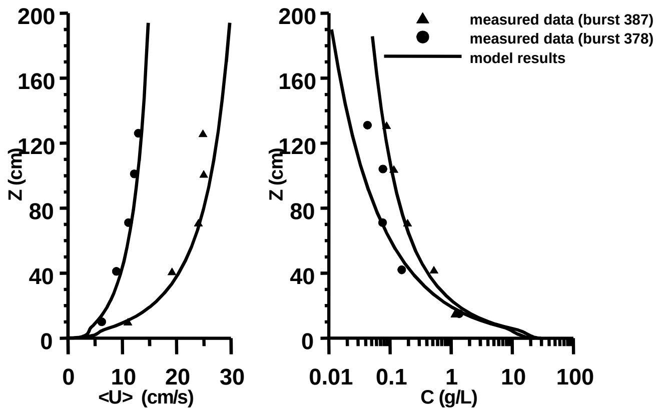

Figure 2. Comparison of simulated data to profiles collected by Wright (1999).

Figure 3 compares predicted and measured time series of near-bed suspended sediment concentrations during the deployment. The agreement is generally good over the duration of the time series, providing further validation of the model in addition to vertical profiles of concentration.

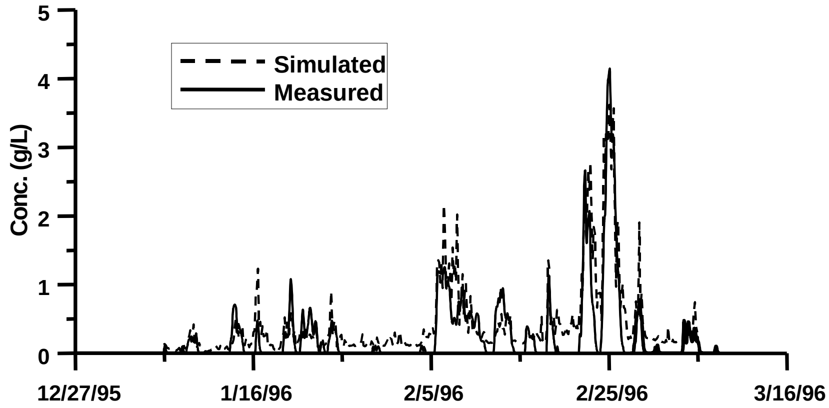

Figure 3. Comparison of near-bottom suspended sediment time series data.

4. Application to St. Marys Entrance Channel

USACE dredging and surveying data from the approach channel at St. Marys Entrance, FL-GA, provide an excellent field-scale test for M3D predictive capabilities. Twenty years of channel cross-section data along the offshore extent of the channel are available, together with dredging records, detailed grain size analysis, and wind, wave and current data (Kraus et al 1995; Johnston et al. 2002). Records indicate that the dredging requirements vary along the channel. Near the inlet entrance and within and just offshore of the ebb tide shoal, the sediment is primarily sand, and the dredging requirements are moderate (~8,000 cy/yr/200 ft of channel). Further offshore, in deeper water, the sediment becomes more silty, and the dredging requirement is greater (~ 20,000 cy/yr/200 ft of channel). In deeper water and silty sediments, the dredging requirements decrease substantially (~500 cy/yr/200 ft of channel).

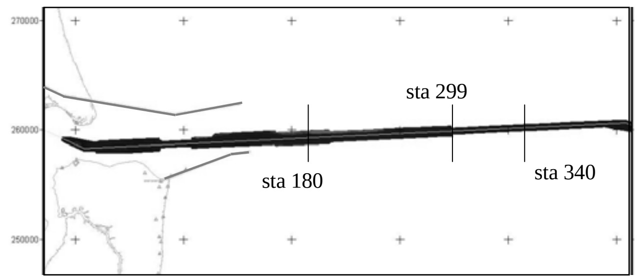

Figure 4. Station locations along deep-draft channel at St Marys Entrance.

The M3D model was configured to simulate channel performance for three channel cross-sections, representing each of the three dredging requirements described above. Figure 4 shows the offshore footprint of the 55-ft (16.8 m) deep channel and the cross-sections used for comparisons. The three-dimensional grid and bathymetry are shown in Figure 5. The bathymetric data were developed by combining data from numerous surveys in the area conducted during the 1990s. Other data were obtained from the GEODAS database maintained by the NOAA National Geophysical Data Center.

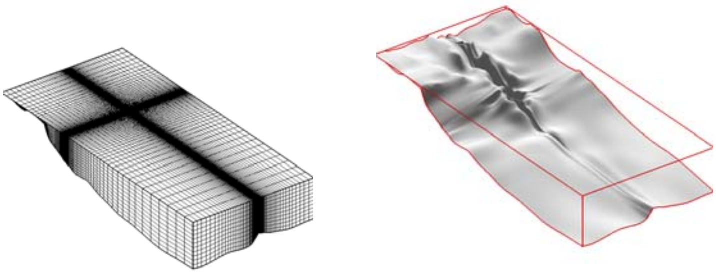

Figure 5. Area bathymetry and three-dimension numerical grid used in M3D.

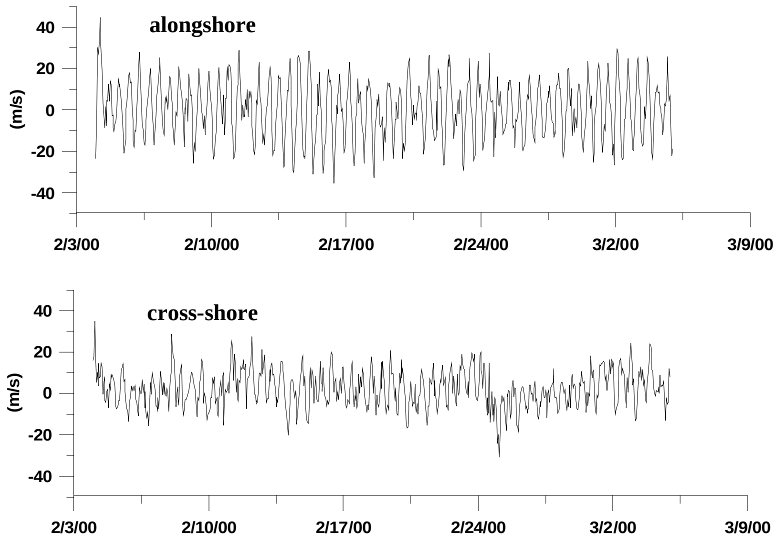

Figure 6. Example of current data used to force the model simulations.

Ten-month simulations were made, from February through November 2000, using local wave (NOAA Buoy 41008) and tidal currents from a regional ADCIRC simulation (Johnston et al. 2002). Figures 6 and 7 show the first month of forcing data for the currents and waves representative of the entire simulation. The horizontal current pattern is dominated by an approximate 20 cm/s longshore tidal current. The cross-shore tidal current ranges between 5 and 10 cm/s. Non-tidal currents are apparent, but are much smaller. Flow boundary conditions for the alongshore component were developed by adjusting the flow along the lateral offshore boundaries. The flow magnitude was adjusted such that the depth-averaged alongshore speed as shown in Figure 6 was reproduced. The cross-shore boundary condition was developed by imposing an oscillatory head along the offshore boundary. The amplitude of the water elevation was adjusted so that the cross-shore speed shown in Figure 6 was reproduced in the domain interior. Average wave heights are in the range of 1 m, and periods of about 6 s. Wave heights approach 2 m at times.

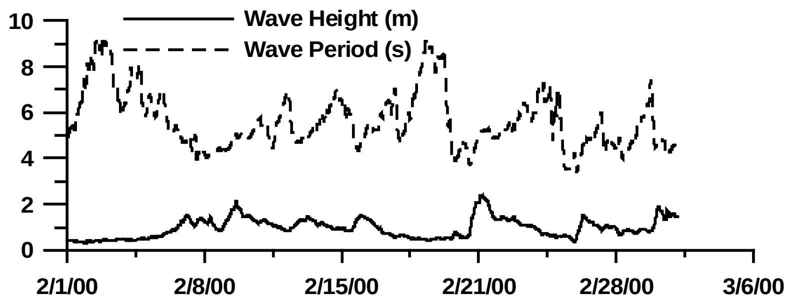

Figure 7. Example wave data input to the M3D simulation.

The three plots in Figure 8 show the initial and final cross-section for the 10-month simulations compared to survey measurements. M3D correctly reproduced the shoal volumes and the offshore volume variations. Most of the increase in shoaling from station 180 to 299 was explained by a change in grains size characteristics (settling velocity and critical erosion stress). The same grain size characteristics were used for simulating transport at station 299 and 340, and the decrease in shoal volume at station 340 was primarily due to decreased bottom stress and the smaller channel depth. The smaller channel depth reduces the contrast between ambient bed and channel bottom hydrodynamic forcing and, subsequently, the smaller transport gradient yields a lower shoaling rate. In the three simulations, the hydrodynamic forcing was nearly symmetric (tidal); therefore, no channel migration occurred.

The shoaling cross-sections predicted by the model deviate slightly from the measurements for the three sites, revealing a systematic variation in character. At station 180, the measurements show a strong asymmetry attributed to near-shore effects of the coastline, ebb shoal, and jetties. The model simulation does not reproduce the same level of asymmetry that is likely due to the approach taken to represent flows at the lateral boundaries. The flow boundary conditions were developed by applying the flow field from one point (taken form the ADCIRDC simulation) and applied along the entire boundary. Furthermore, the affects of littoral currents were not included in this simulation. At stations 299 and 340, the break from the ambient seabed to the channel tends to be rounded more in the model simulations. At the base of the channel, the simulations tend to produce a curved profile, whereas the surveys are flatter. These systematic variations in profile shape warrant further analysis and may be due to differences in partitioning in bedload and suspended load between the actual and modeled processes, as well as to geomorphic constraints in tidal inlet morphology (Buonaiuto and Kraus (2003). .

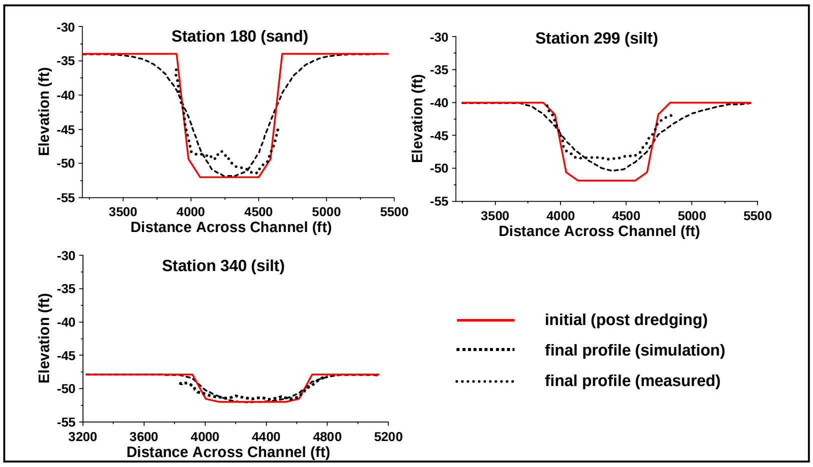

Figure 8. Measured and simulated channel infilling at three stations along the deep-draft channel

5. Conclusions

The M3D model was developed to provide predictive capabilities for assessing channel designs and performance with regard to channel infilling and migration. M3D was created by combining the M2D circulation model (Militello et al., 2004) developed under the USACE CIRP and the SLICE model developed as part of the ONR STRATAFORM project (Nittrouer, 1999). The M3D model is a three-dimensional extension of the M2D depth-averaged technology.

The M3D model hydrodynamic and sediment transport components were tested against numerous data sets. They successfully reproduced the time-dependent flow and suspended sediment transport measurements in flow tunnel experiments of Ribberink, et al. (1994) and the flow and suspended sediment vertical profiles and time series data from the field experiments of Wright (1999). Only a small portion of the validation could be presented here.

M3D successfully simulated in-filling rates at the St. Marys Entrance deep-draft navigation channel, demonstrating the influence of water depth and grain size on calculated sediment transport rates. The documented systematic decrease in shoaling rate with distance offshore (Johnston et al., 2002) was properly simulated with the model and can be explained by the dependence of bottom stresses on water depth and the ambient grain size.

Acknowledgments

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Channel Shoaling
Channel Migration
3D hydrodynamic Modeling
Sediment Transport Modeling
Morphodynamic Modeling
Inlets
St. Mary’s Entrance Channel
M2D model
M3D model